Highlights of the XENON program

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16th Rencontres du Vietnam

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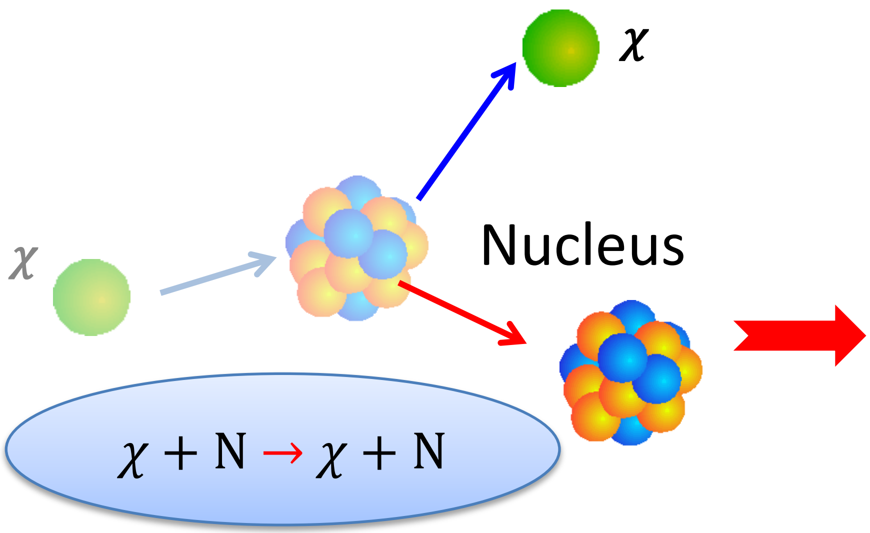
ICISE

Theory meeting experiment

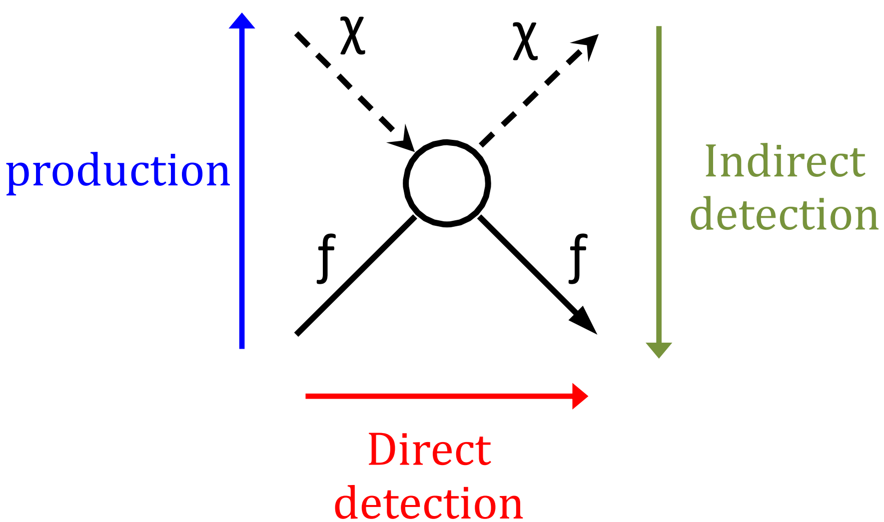
2020

WIMP direct detection principle

Nuclear Recoil (NR)



Recoil energy
~1-100 keV

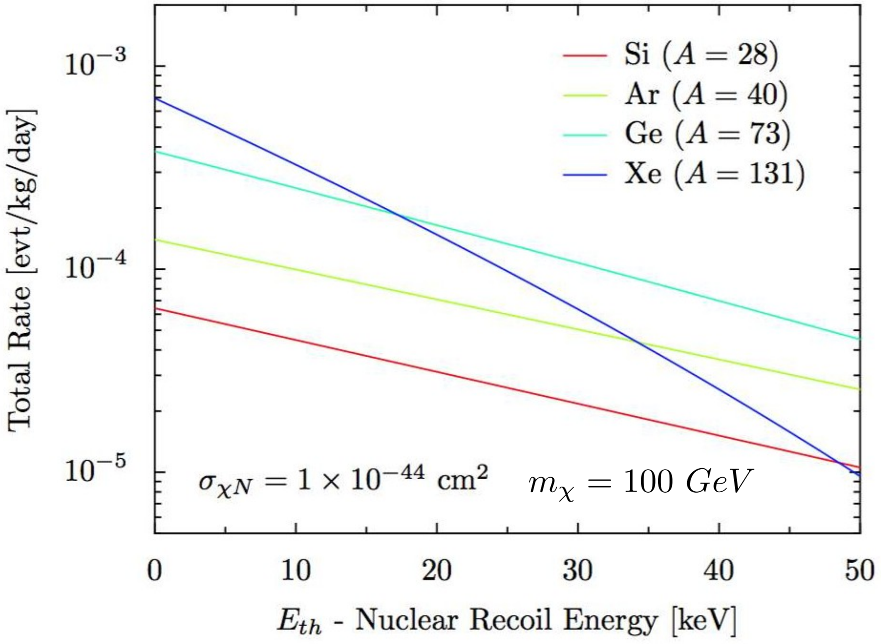


Electronic Recoil (ER)

γ and β particles interact with the atomic electrons
➔ Background in « standard WIMP analysis »

Why Xenon ?

- Large mass number A (131) (Interaction cross section ∝ A^2)
- 50% odd isotopes (^{129}Xe, ^{131}Xe) for Spin-Dependent interactions
- Kr can be reduced to ppt levels
- High stopping power, i.e. active volume is self-shielding
- Efficient scintillator (178 nm)
- Scalable to large target masses
- Electronic recoil discrimination with simultaneous measurement of scintillation and ionization



XENON Collaboration

~ 160 scientists

28 institutions

11 countries

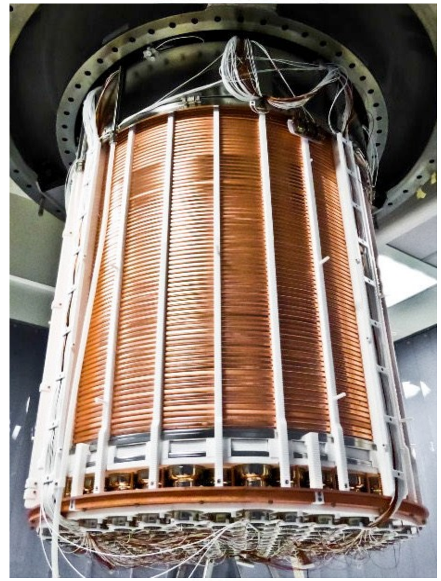
Phases of the XENON Program

XENON10
2005 – 2007
15 cm drift TPC
Total: 25 kg
Target: **14** kg
Fiducial: 5.4 kg

Achieved (2007)
$\sigma_{SI} = 8.8 \cdot 10^{-44}$ cm^2
@ 100 GeV/c^2

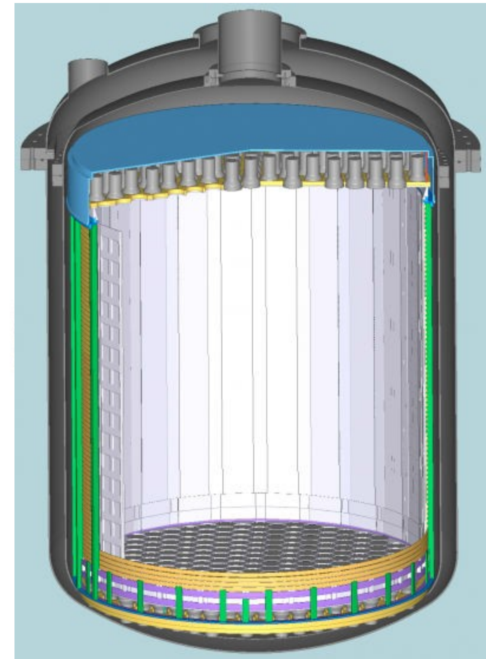
XENON100
2008 – 2016
30 cm drift TPC
Total: 161 kg
Target: **62** kg
Fiducial: 34/48 kg

Achieved (2016)
$\sigma_{SI} = 1.1 \cdot 10^{-45}$ cm^2
@ 55 GeV/c^2



XENON1T
2011 – 2018
100 cm drift TPC
Total: 3 200 kg
Target: **2 000** kg
Fiducial: 1 300 kg

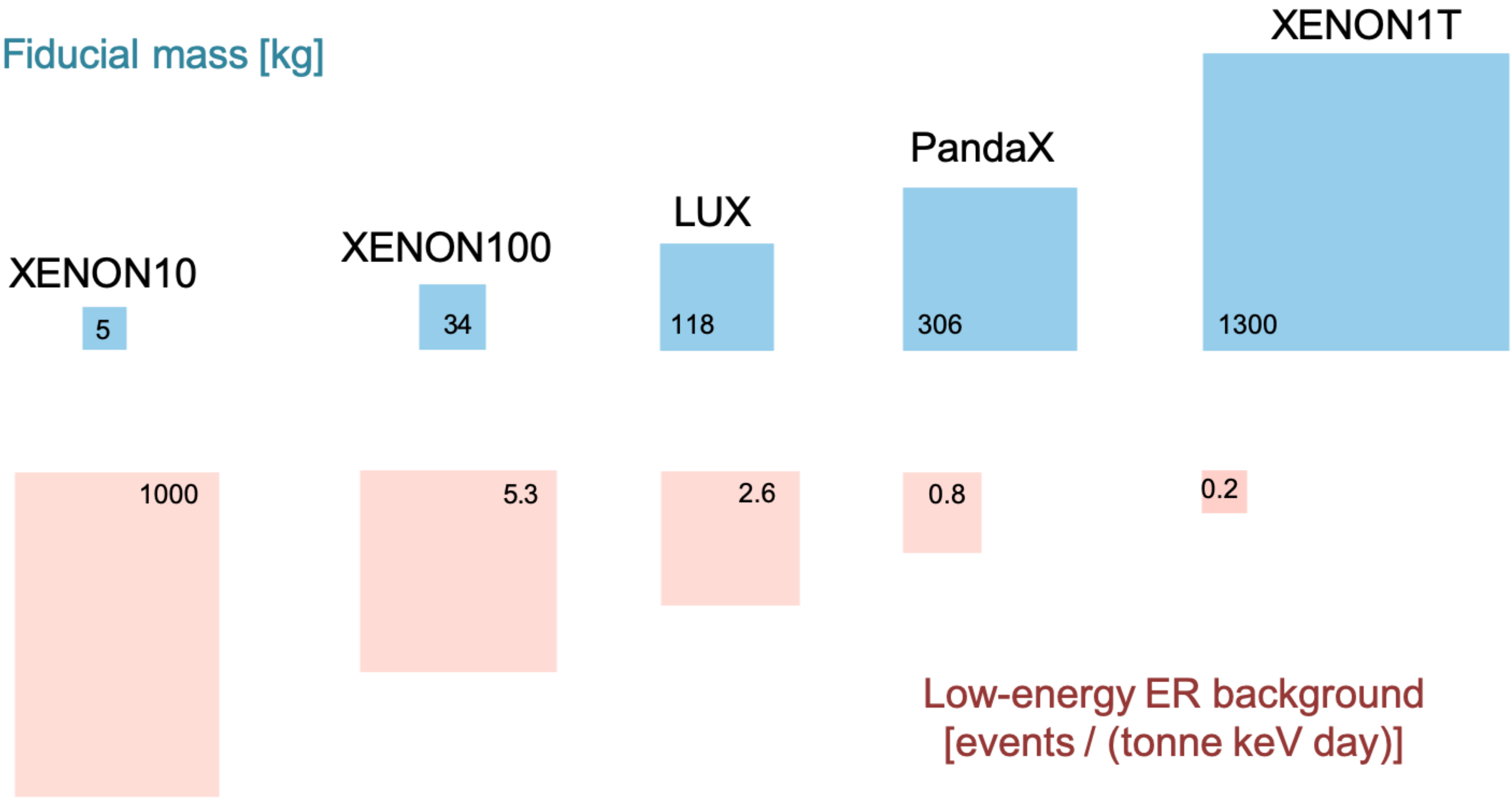
Achieved (2018)
$\sigma_{SI} = 4.1 \cdot 10^{-47}$ cm^2
@ 30 GeV/c^2



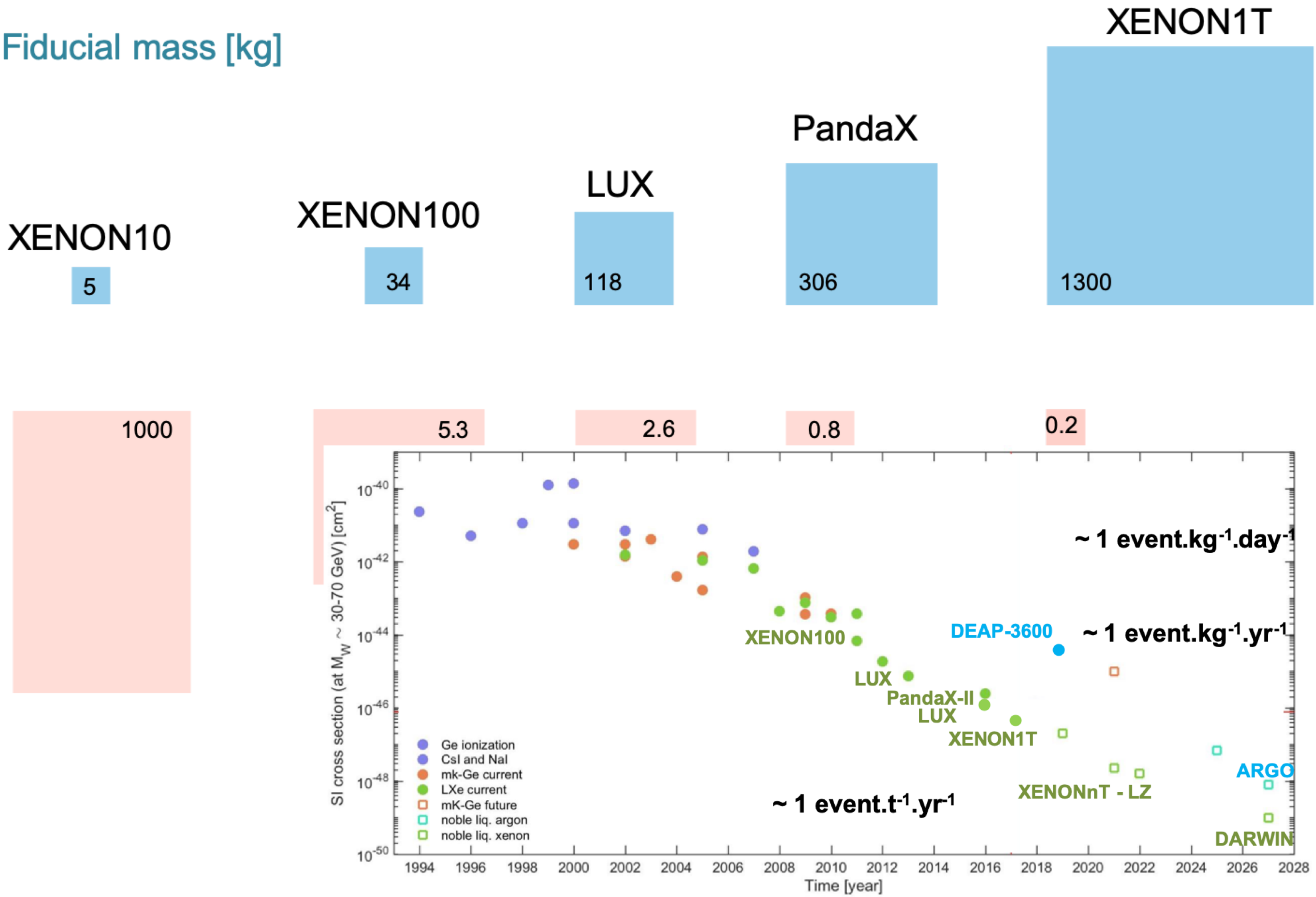
XENONnT
2019 – 2025
150 cm drift TPC
Total: 8 400 kg
Target: **5 900** kg
Fiducial: ~ 4 000 kg

Projected
$\sigma_{SI} = 1.6 \times 10^{-48}$ cm^2
@ 50 GeV/c^2

Evolution of LXe TPC as WiMP detectors

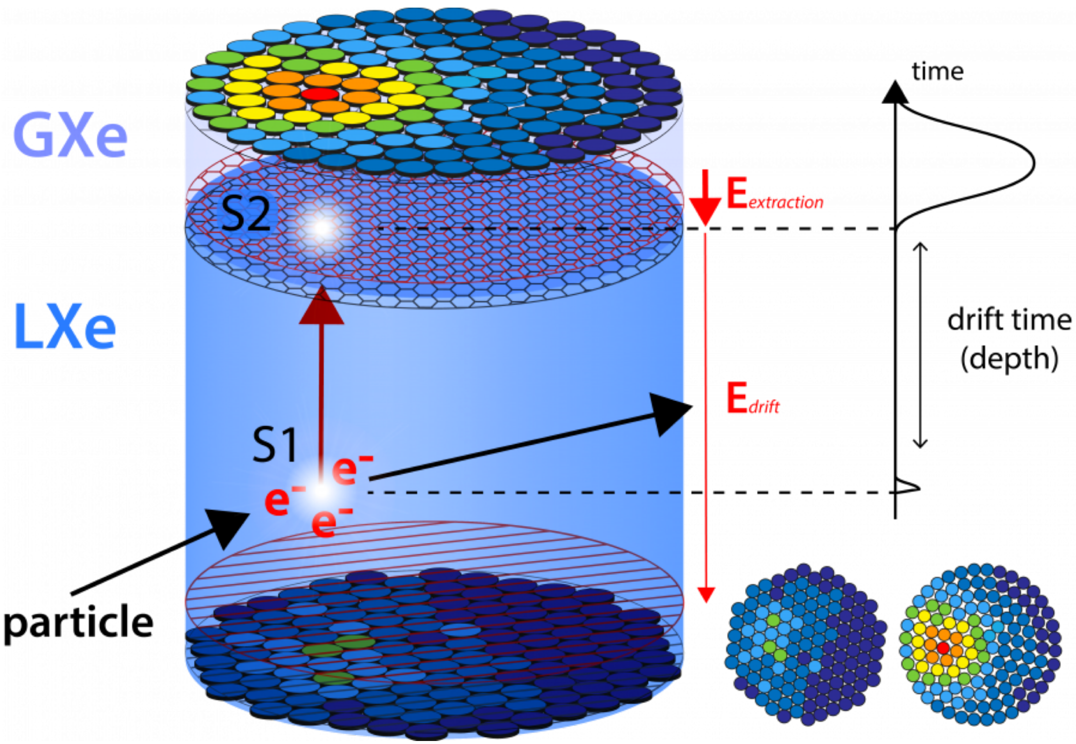


Evolution of LXe TPC as WiMP detectors



Dual phase TPC: principle

TPC = Time Projection Chamber

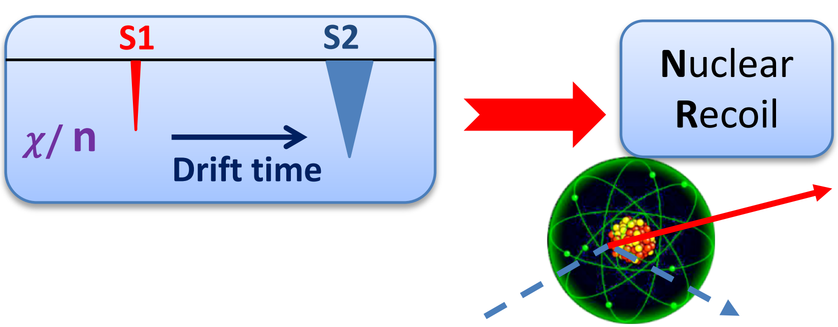


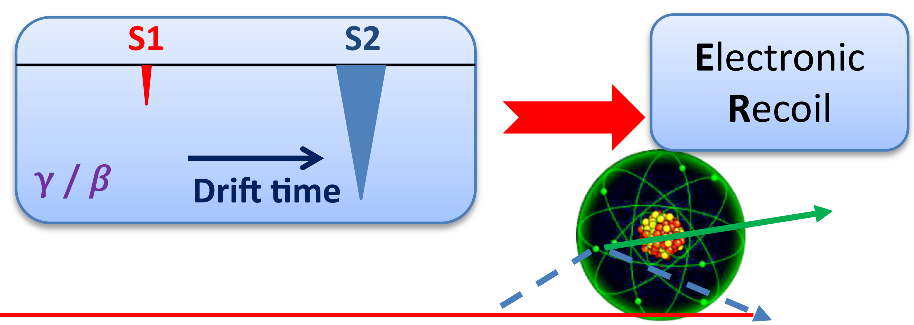
S1:
→ Photon (λ = 178 nm) from Scintillation process

S2:
→ Electrons drift
→ Extraction in gaseous phase
→ Proportional scintillation light

3D reconstruction :
→ X,Y from top array
→ Z from Drift time

$$(S2/S1)_{WIMP,n} < (S2/S1)_{\gamma,\beta}$$





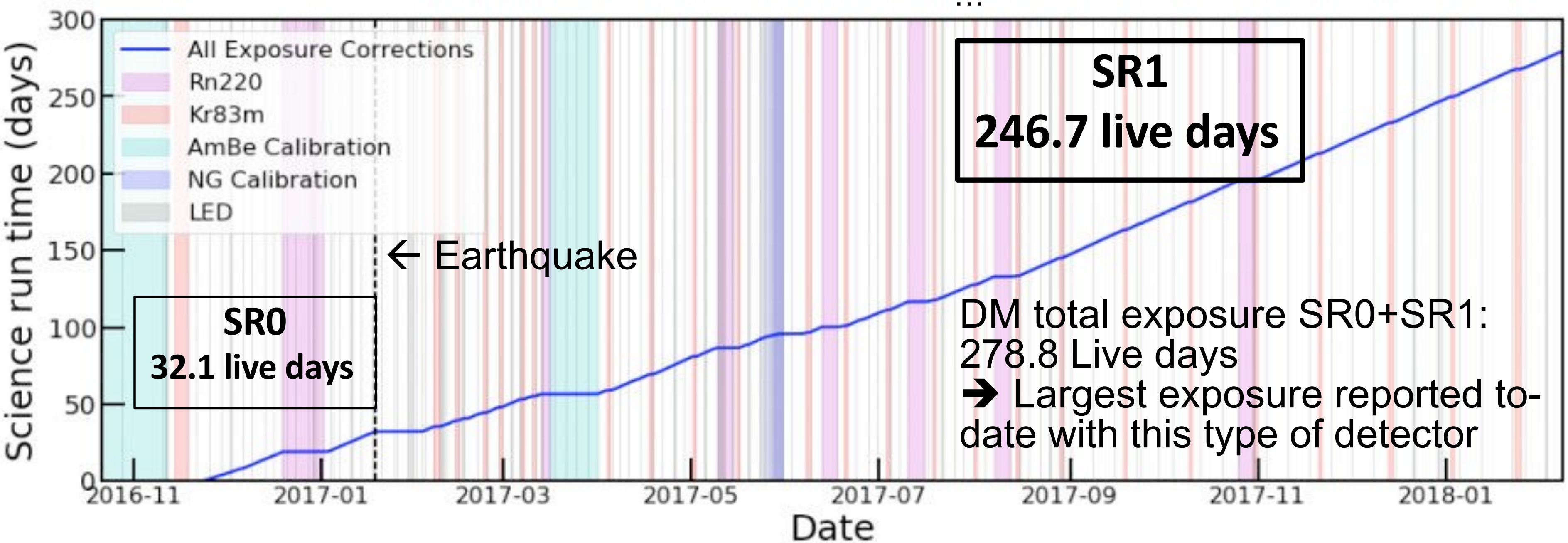
Uses of S1 & S2 with data

- "Standard" nuclear recoil WIMPs models:
  - SI WIMP-nucleon interactions
  - SD WIMP-nucleon interactions
  - Low mass WIMPS
  - …

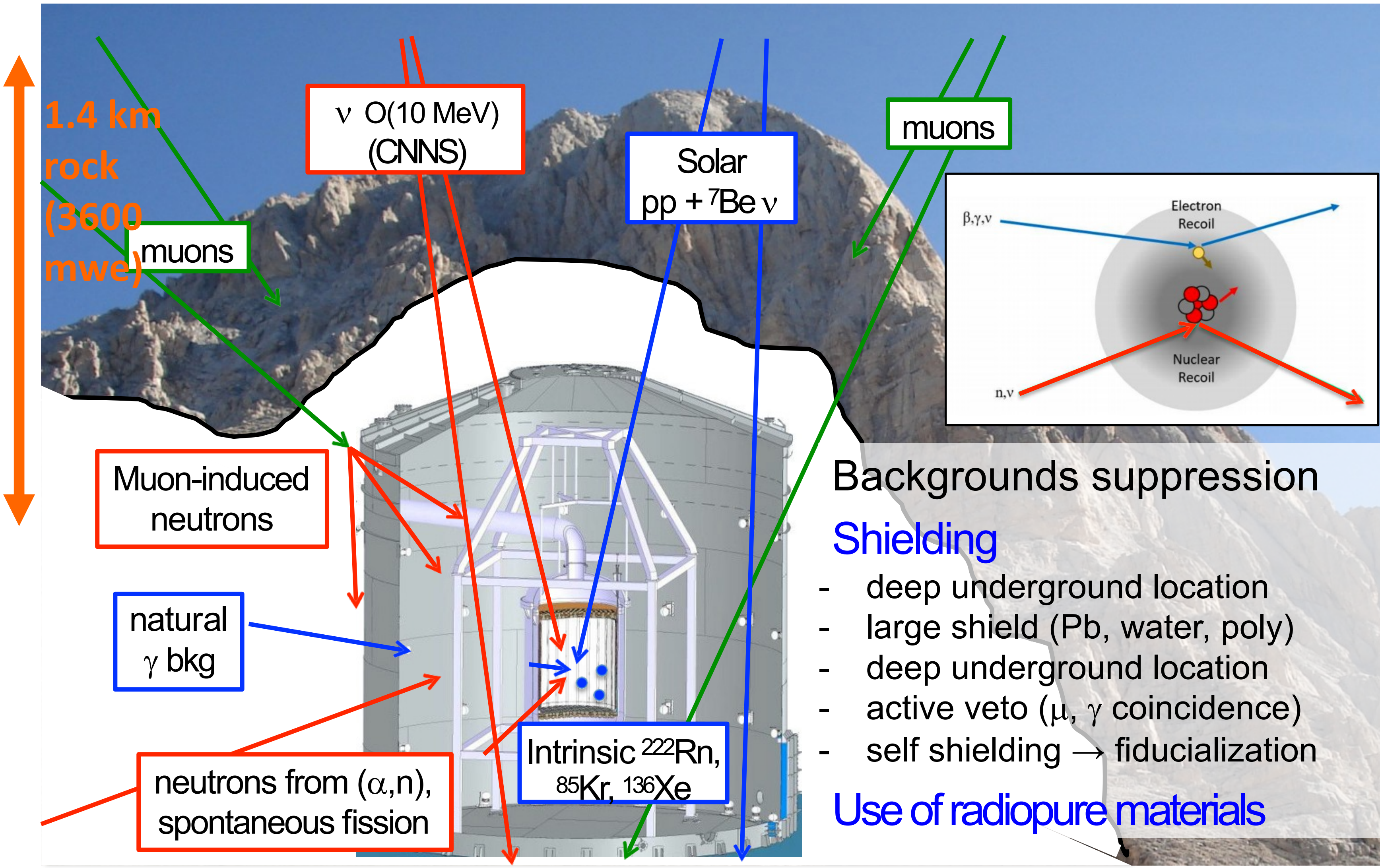
- DM-electron scattering:
  - Solar axions
  - Axion-like particles (ALPs)
  - …

- Leptophilic models:
  - Annual modulation
  - Exotic models: WIMP axial-vector coupling to electrons,
    mirror dark matter, luminous dark matter
  - …

- Neutrino physics:
  - 0νββ decay with 136Xe
  - 2ν double electron capture with 124Xe
  - …



Origins of backgrounds



Backgrounds suppression

Shielding

- deep underground location
- large shield (Pb, water, poly)
- deep underground location
- active veto (μ, γ coincidence)
- self shielding → fiducialization

Use of radiopure materials

XENON1T facility

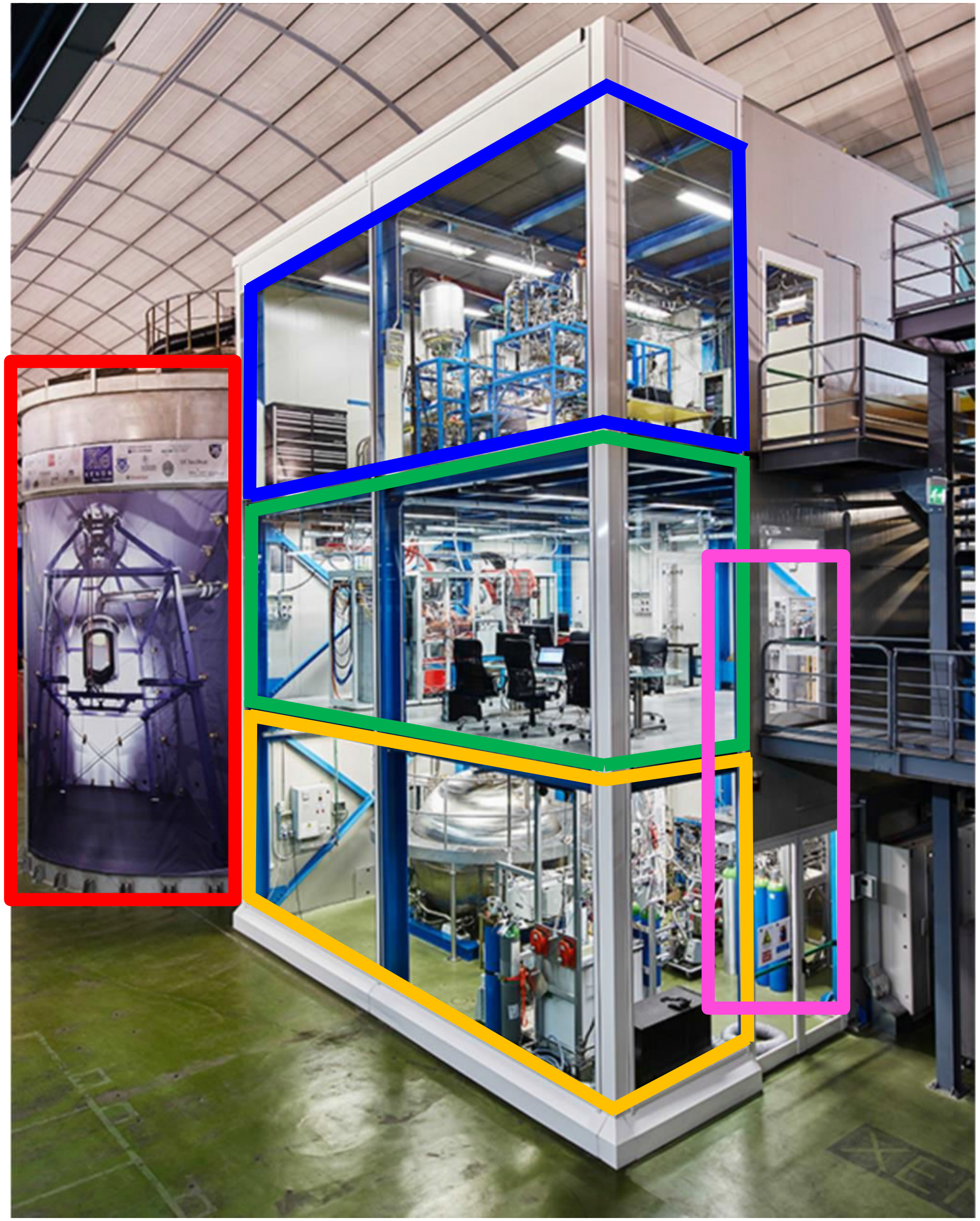
Water shield: deionized water as passive radiation shield
Muon veto: Active muon veto against muon induced neutrons (84 PMTs)

Cryogenics: Stable conditions (3.2 LXe)
Purification: LXe flow through getters, remove impurities

DAQ: Each channel has its own threshold, Flexible software algorithms
Readout: Up to 300MB/s for high rate calibrations

ReStoX: Emergency recovery up to 7.6 tons of LXe
Passive: No active cooling required to keep Xe contained

Kr Distillation: Remove Kr from system during fill or online
Rn Distillation: Initial tests show promising reduction for Rn



Electronic Recoil Background

4.1% Materials

- HPGe γ screening: material selection
- Suppressed by fiducialisation

1.4% ^{136}Xe

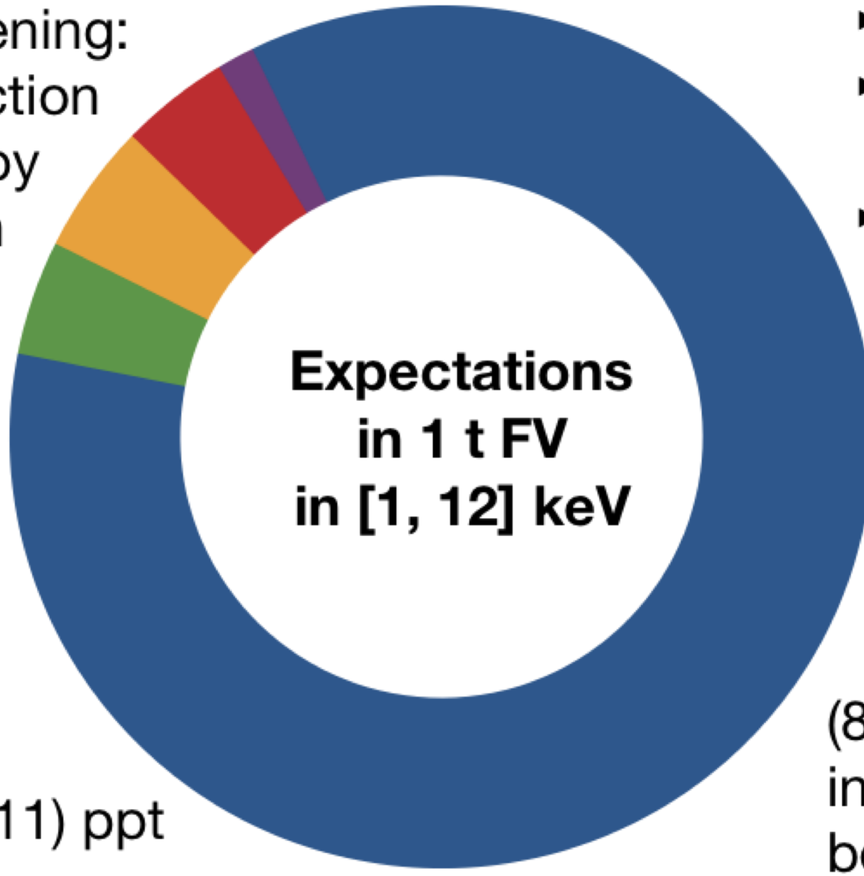
85.4% ^{222}Rn

- ~ 10 μBq/kg
- Control surface emanation
- Further reduction by online distillation (more later)

4.9% Solar ν

4.3% ^{85}Kr

- Cryogenic distillation
- ^{nat}Kr (0.66 ± 0.11) ppt



ER Rate

(82 ± 5) ev/(keV t y)
in 1.3 t
below 25 keV$_{ee}$

Lowest ER background ever achieved in DM detector

JCAP04 (2016) 027

Nuclear Recoil Background

< 0.01 ev Cosmogenic n

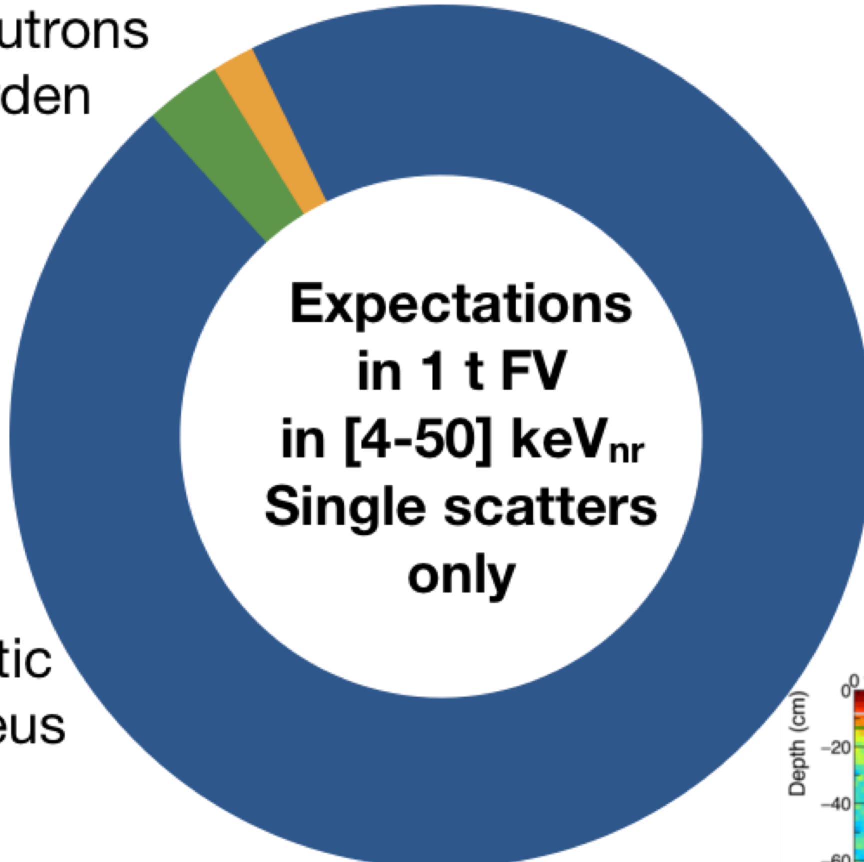
- μ-induced neutrons
- Rock overburden
- Muon veto

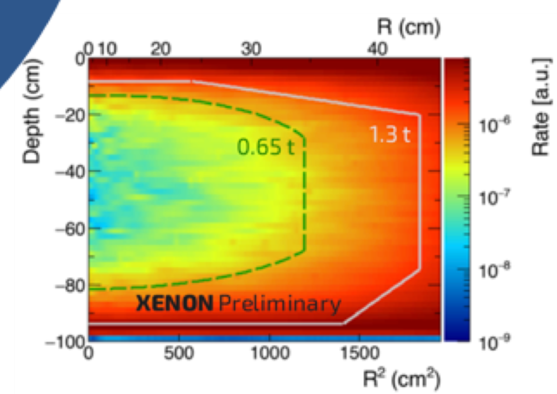
JINST 9:P11006 (2014)

0.6 ev Radiogenic n

- From (α, n) and spontaneous fission
- Material selection
- Mostly multiple scatter
- Fiducialisation

EPJ C 77:890 (2017)





0.02 ev CEνNS

- Coherent elastic neutrino-nucleus scattering of ^{8}B solar ν
- Irreducible, very low energy (< 1 keV)

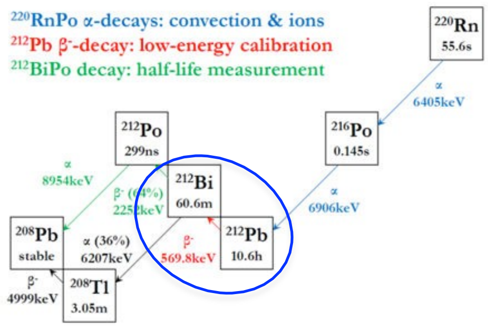
JCAP04 (2016) 027

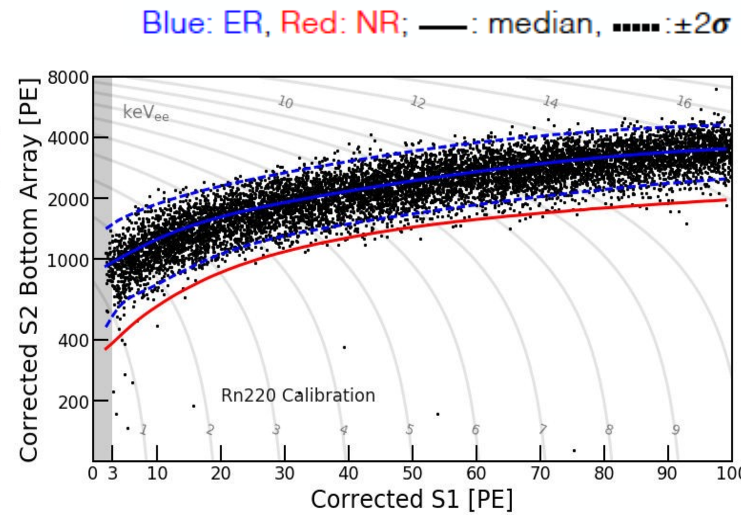
Calibrations

Electronic Recoils

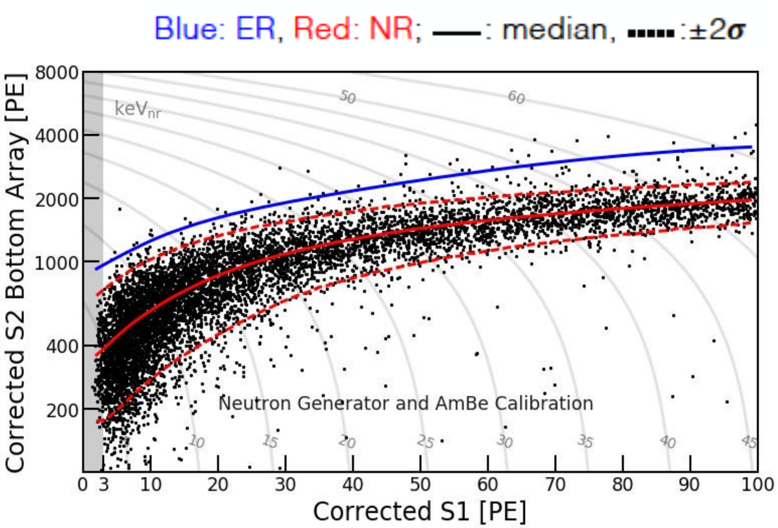
Internal source

- ^{228}Th source emanates **^{220}Rn** into LXe
- **β-decay** of ^{212}Pb to ^{212}Bi
  ➔ **Low energy** events (2–20 keV)
- Decay of activity dominated by ^{212}Pb half-life (10.6 h)

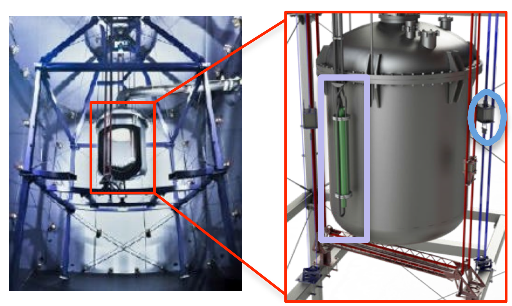




Nuclear Recoils

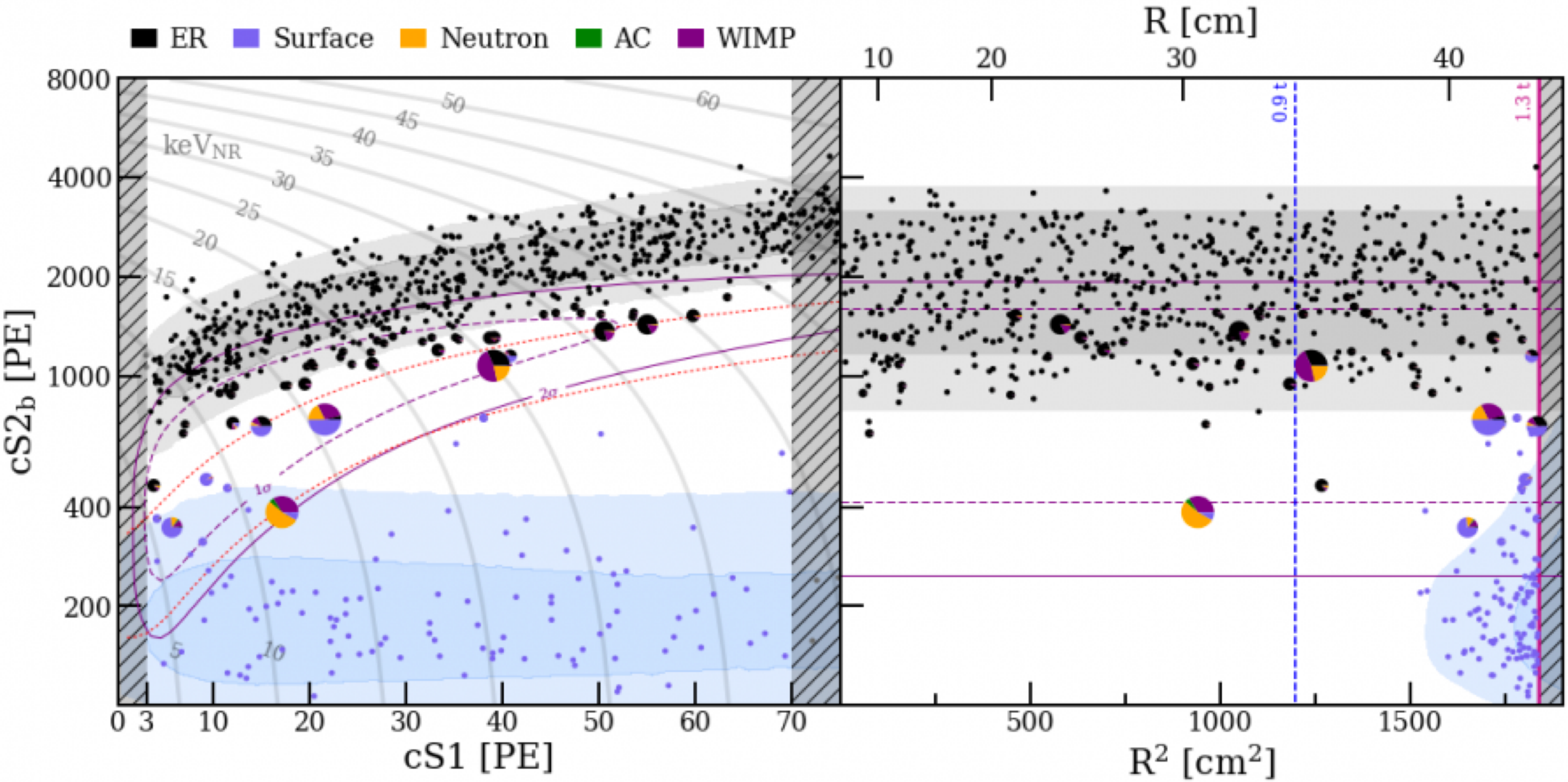


External source



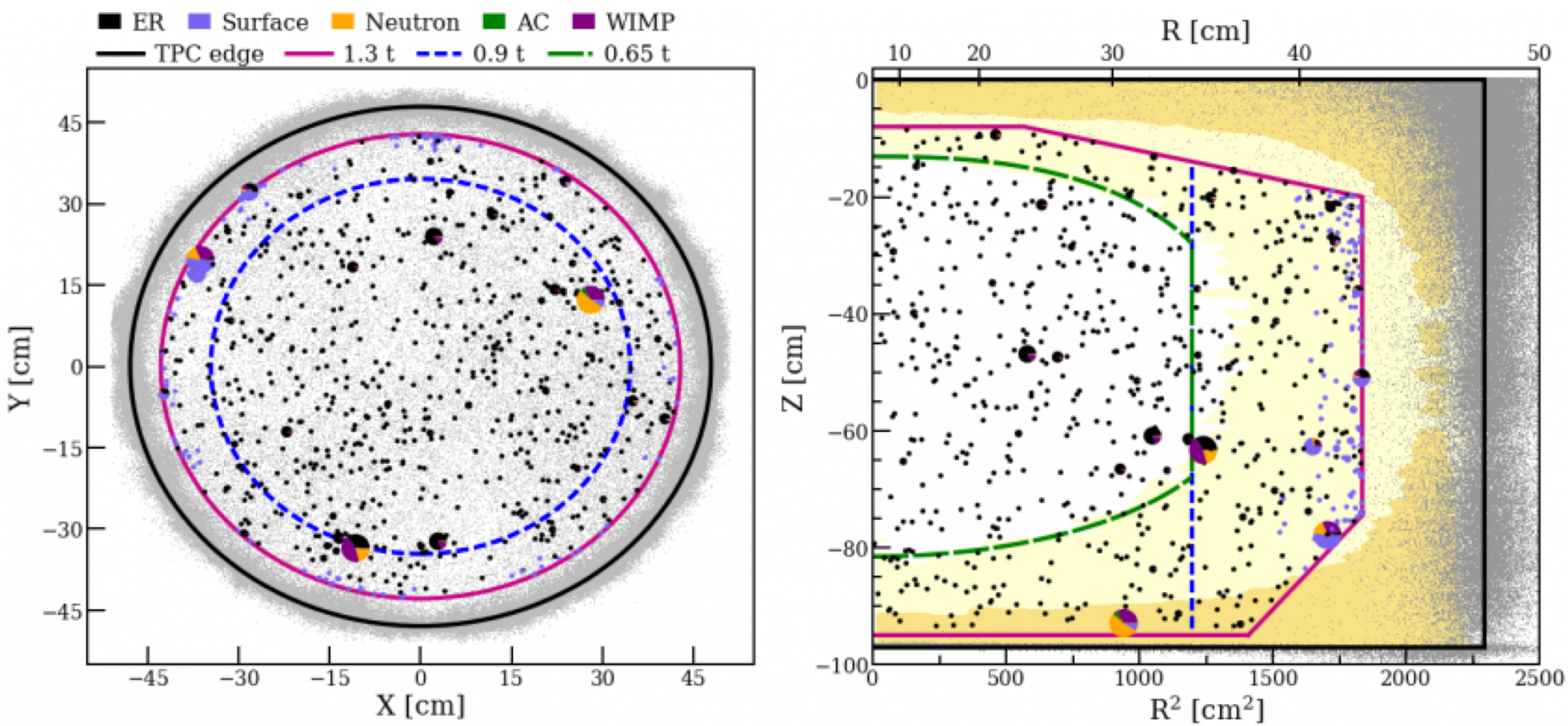
- External **^{241}AmBe** source mounted on a belt
- The α particles emitted by the decay of the Am collide with the light Be nuclei producing fast neutrons
- **Neutron Generator**

Dark Matter Search Results



- Results interpreted with unbinned profile likelihood analysis in cs1, cs2, R space
- Pie chart indicate the relative probabilities of this event to be of a certain class for a best fit to a 200 GeV/c^2 WIMPs with a cross-section of 4.6 x 10^{-47}cm^2

Spacial Distribution of Dark Matter Search Results



- Core volume to distinguish WIMPs over neutron background
- Yellow shaded regions display the 1σ (dark), and 2σ (light) probability density percentiles of the radiogenic neutron background component

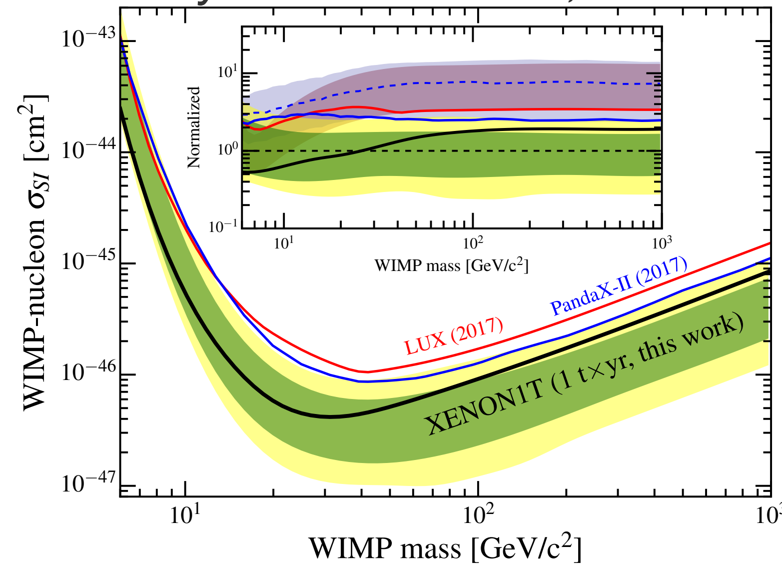
Limits on WIMP cross-section

Spin independent analysis:

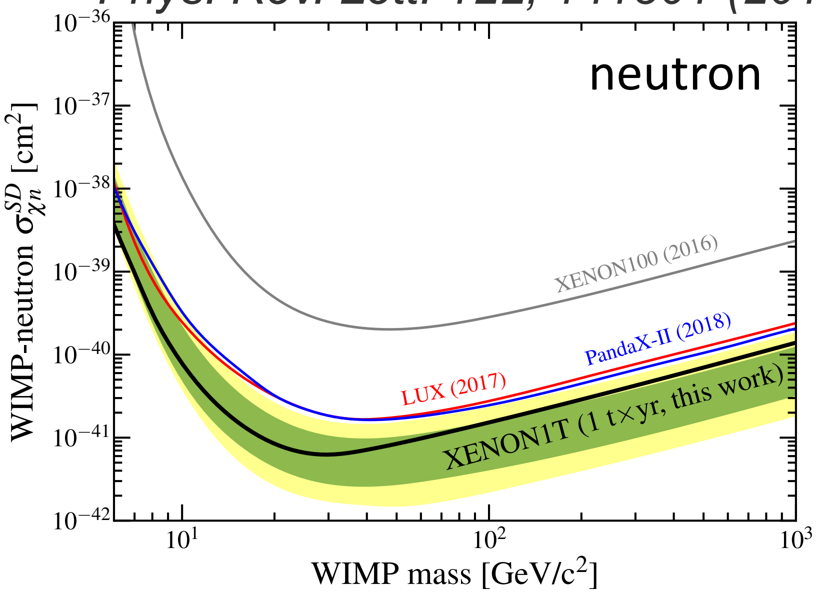
- Sensitivity 7 times improvement over previous experiments
- Strongest exclusion limits (at 90% CL) on WIMPs > 6 GeV/c^2.
- Minimum at 30 GeV : **σ_{SI} < 4.1.10^{-47} cm^2**

Phys. Rev. D 100, 052014 (2019)
Phys. Rev. D 99, 112009 (2019)
JINST 14 (2019) no.07, P07016

Phys. Rev. Lett. 121, 111302



Phys. Rev. Lett. 122, 141301 (2019)



Spin dependent analysis:

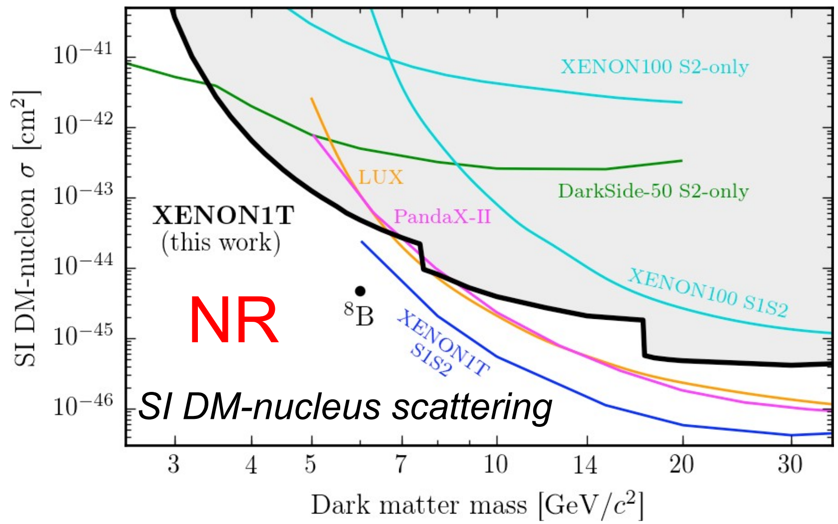
- Odd-nucleon isotopes in ^{nat}Xe, abundance:
  - ^{129}Xe 26.6%
  - ^{131}Xe 21.2%
- Same data and quality criteria as for SD analysis
- Most stringent limit for WIMP-neutron scattering

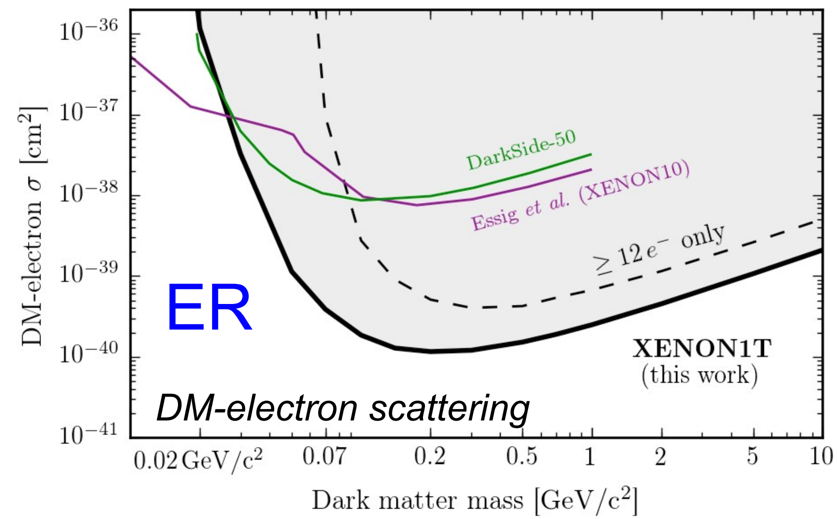
Light Dark Matter (S2 only analysis)

- Constraints on light DM model using S2 signal only
  S2-only technique is sensitive to 2-3x lower energies than traditional analyses

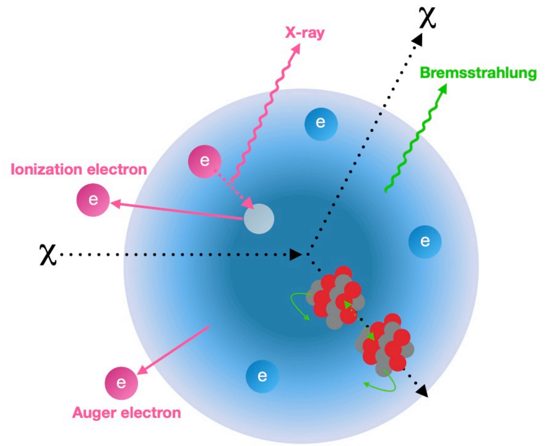
- In some models, DM collides with electrons : ER
- much larger S2 signals than NR of the same S1 size
- S2-only searches improve the energy threshold for these models by as much as a factor of ten.

Phys. Rev. Lett. 123, 251801 (2019)



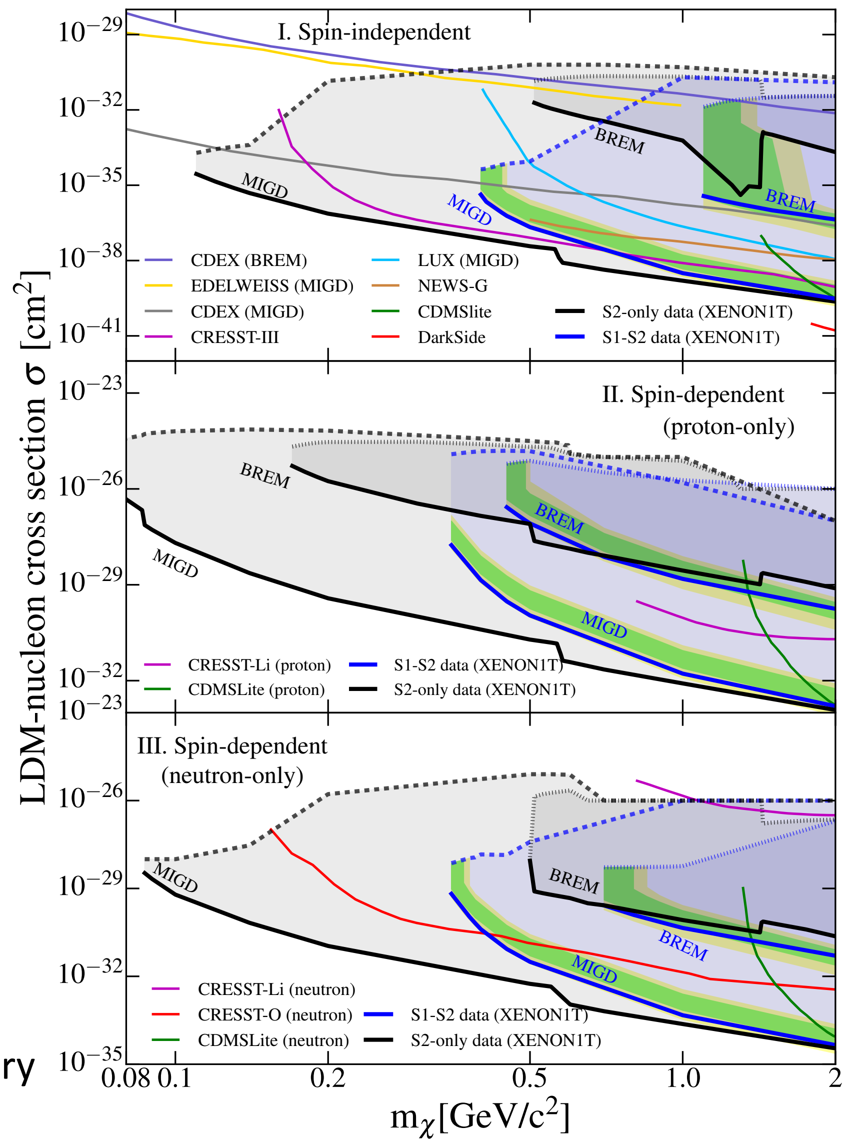


Light Dark Matter (S2 only analysis)



NR
+
ER

Phys. Rev. Lett. 123, 241803 (2019)



Probe of light DM-nucleon elastic interactions:

ER induced by secondary radiation (Bremsstrahlung and Migdal effect) that can accompany a NR

➔ ER induced signal < 1 keV

➔ S2 only analysis

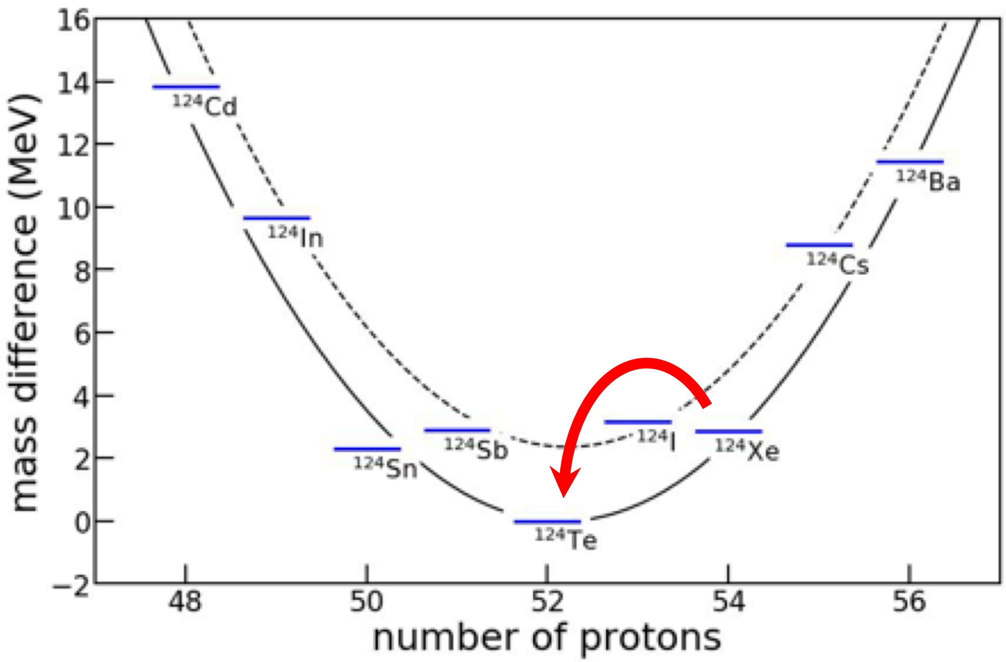
Bremsstrahlung:

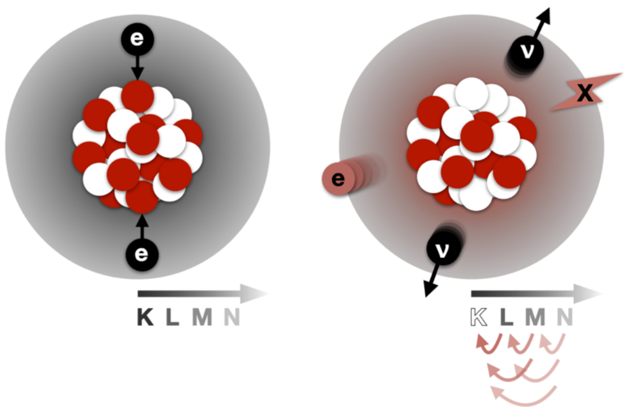
Irreducible contribution that can accompanies scatters by the de-polarization of the atom.

Migdal effect

The process of ionization/excitation of an atom in not instantaneous and the Migdal effect could produce secondary electronic recoils that can accompany a nuclear recoil.

Double electron capture (DEC) with ^{124}Xe





Abundance:
^{124}Xe ~ 1 kg / t

- $^{124}Xe + 2e^- \rightarrow {}^{124}Te + 2\nu_e$
- Vacancies on the K shell : Detectable cascade of X-rays and Auger electrons in the **keV-range (64.3 keV)**
- Large half-lives : > 10^{12}. $T_{univers}$
- Needs very **low background** experiment

XENON1T

Known energy resolution

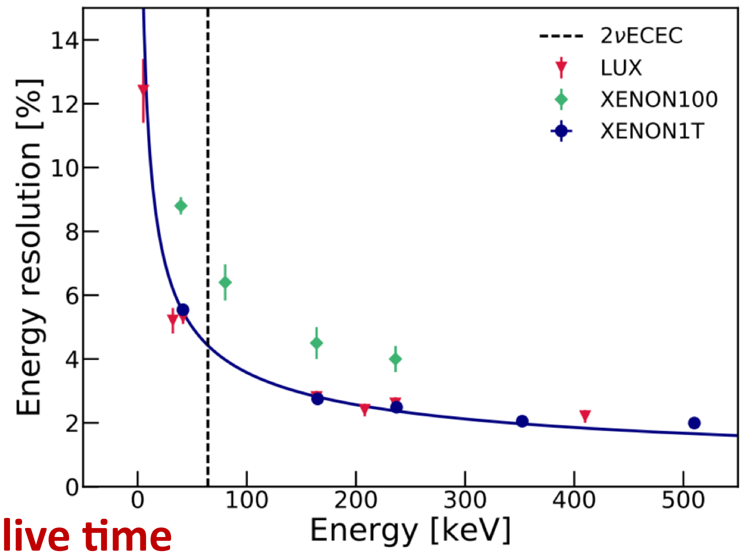
$$\frac{\sigma}{\mu} = (4.1 \pm 0.4)\ \%$$

@ 64 keV

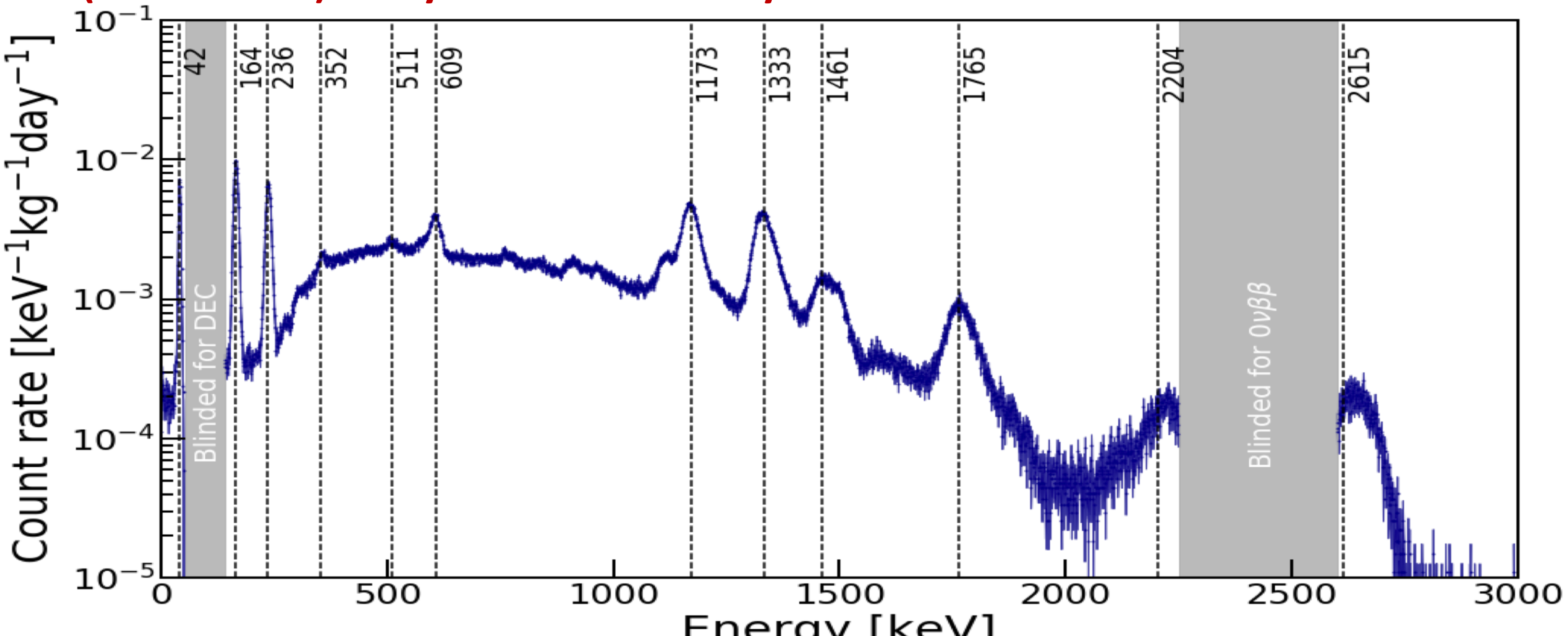
Double electron capture (DEC) with XENON1T

^{124}Xe ⇔ Double K-shell capture :
X-rays and Auger electrons
Single peak @64.3 keV

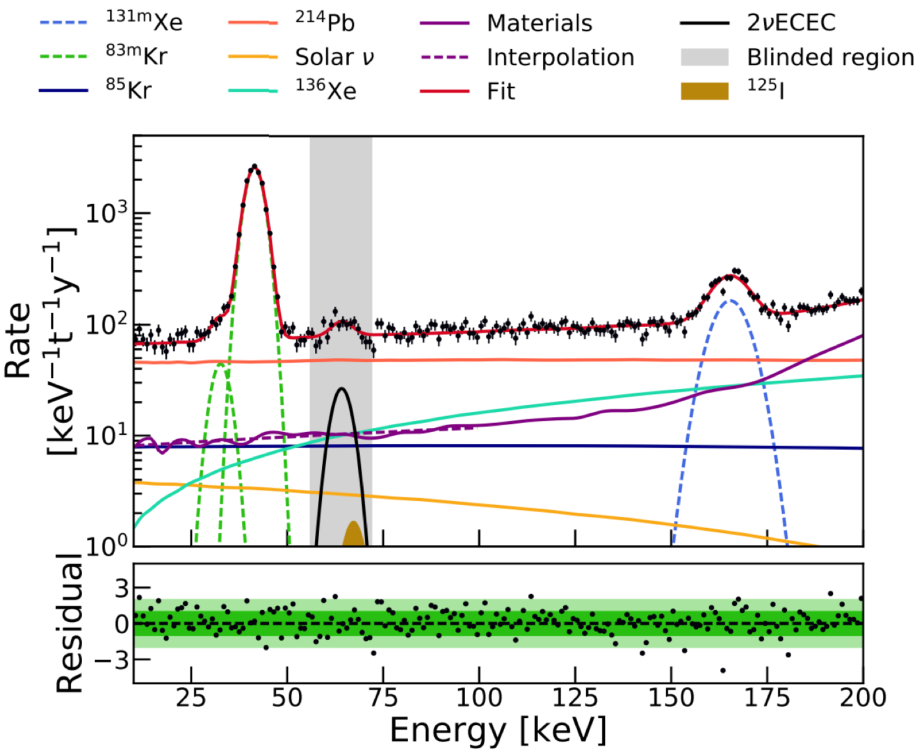
Energy resolution @64.3 keV:
$\frac{\sigma}{\mu} = (4.1 \pm 0.4)\ \%$

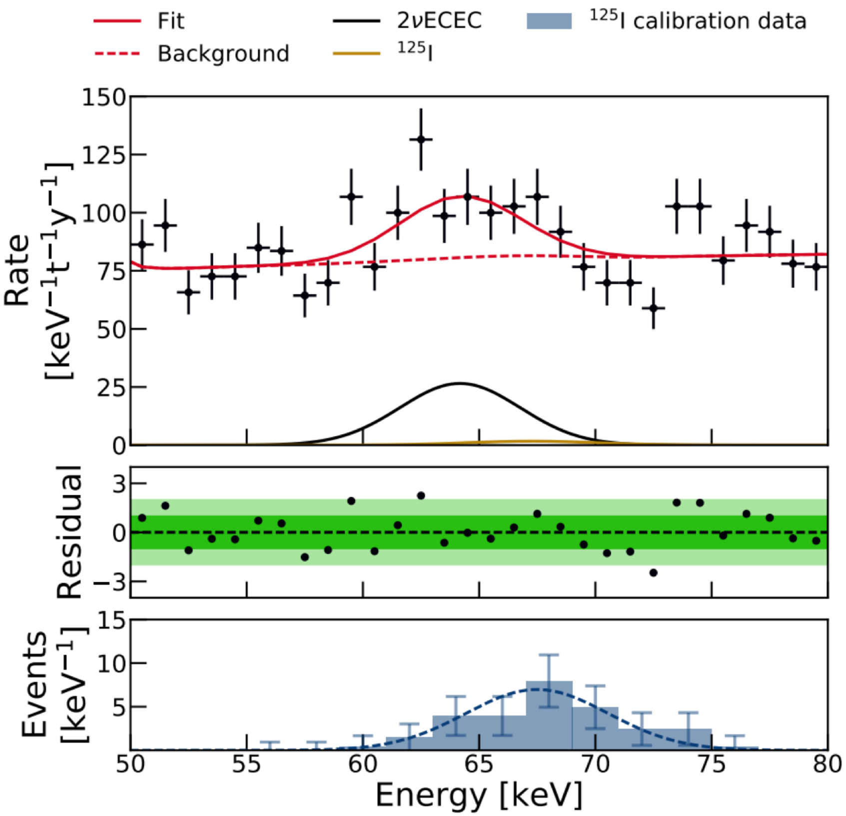


Blinded (56 – 72 keV) analysis with 177.7 days of live time



Double electron capture (DEC) Results





- Blind analysis
- 177.7 live days
- 1.5 ton fiducial
- 1.49 kg of ^{124}Xe

Best fit result:

N_{DEC} = 126 (black)

$N_{I\text{-}125}$ = 9 (gold)

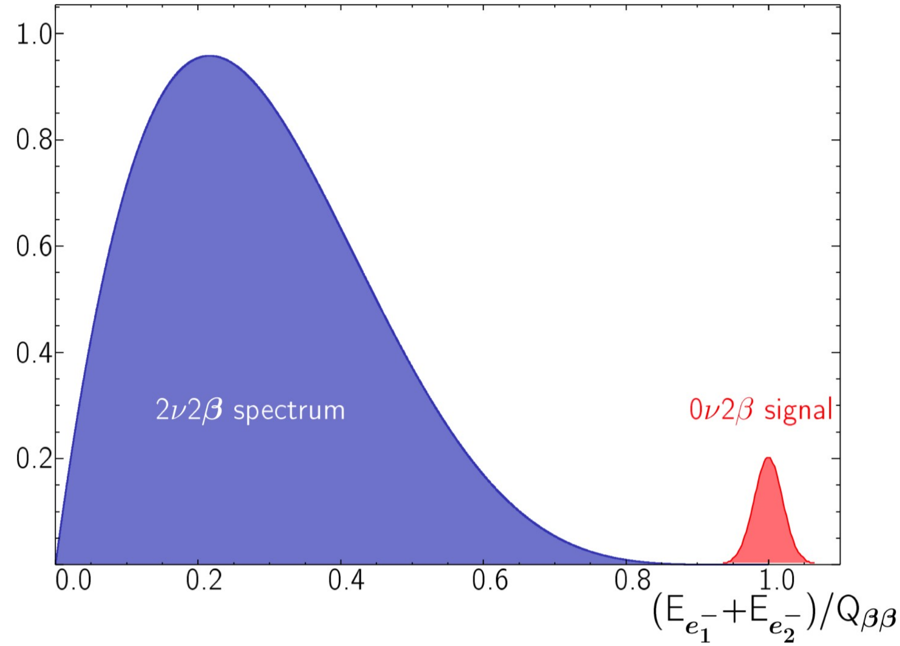
Exclude null hypothesis at 4.4σ

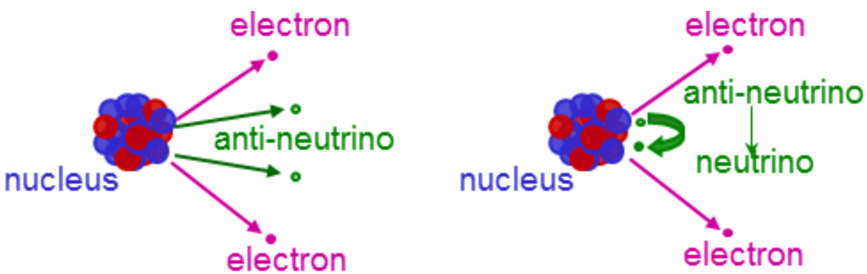
Half-life $T_{1/2} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ y

Nature 568, 532–535 (2019)

High energy analysis for $0\nu2\beta$ search

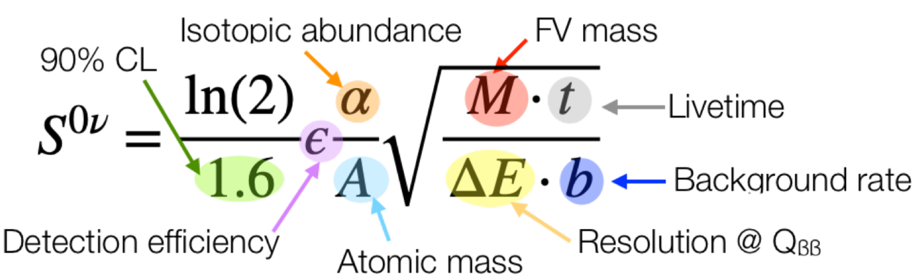
- $^{136}Xe \rightarrow {}^{136}Ba + 2e^- + 2\bar{\nu}$
- $Q_{\beta\beta} = (2457.83 \pm 0.37)$ keV
- Neutrinoless mode:
  $^{136}Xe \rightarrow {}^{136}Ba + 2e^-$
- Best lower limit from KamLAND-Zen:
  $T_{1/2} > 1.07 \times 10^{26}$ yr @ 90% CL



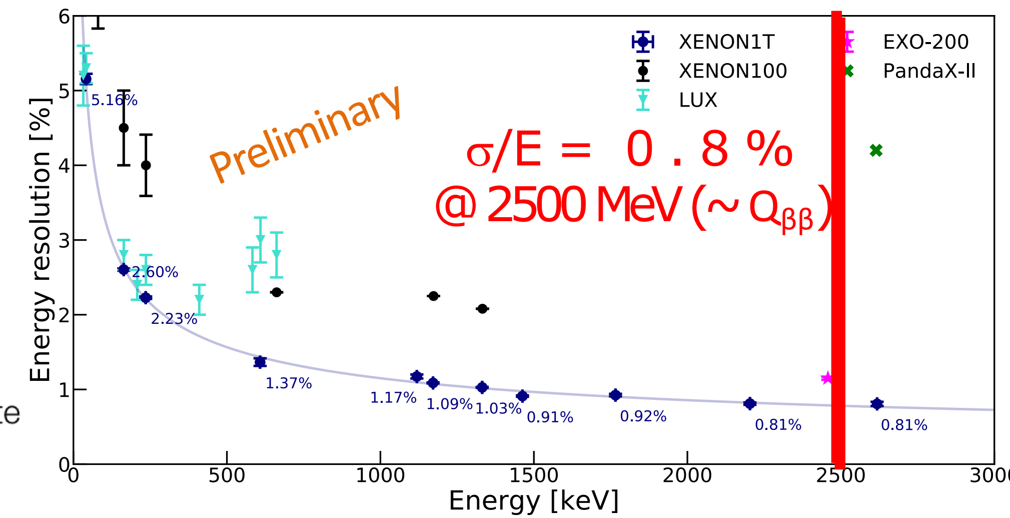


Two neutrino double beta decay

Neutrino-less double beta decay

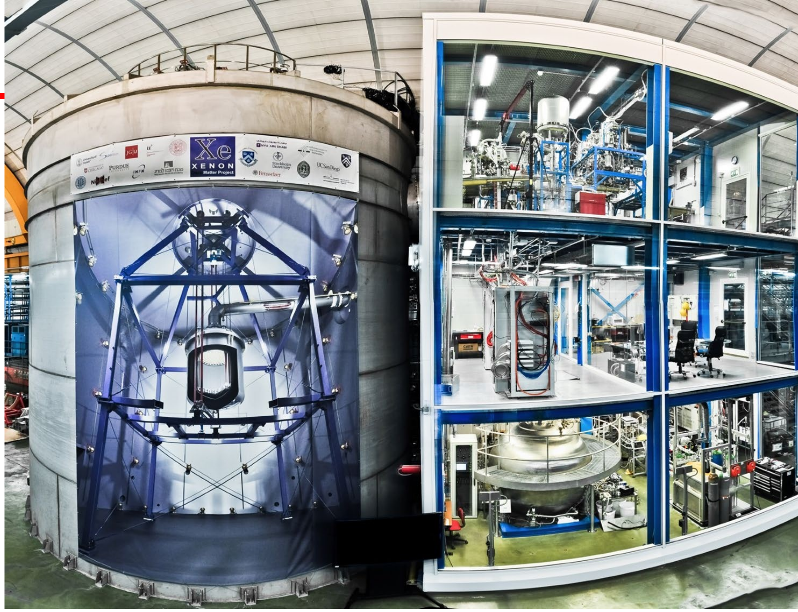


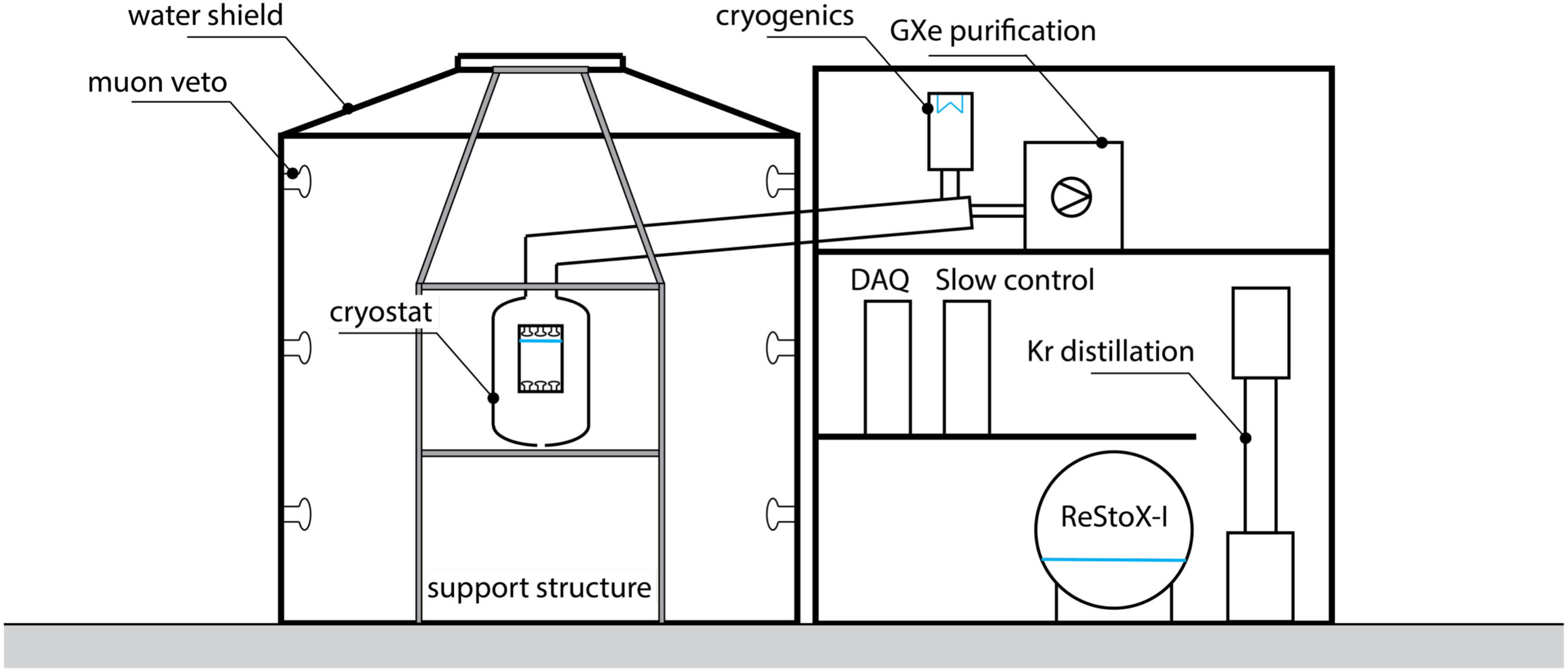
$$S^{0\nu} = \frac{\ln(2)}{1.6}\frac{\alpha\,\epsilon}{A}\sqrt{\frac{M\cdot t}{\Delta E\cdot b}}$$



World best energy resolution in a LXe detector

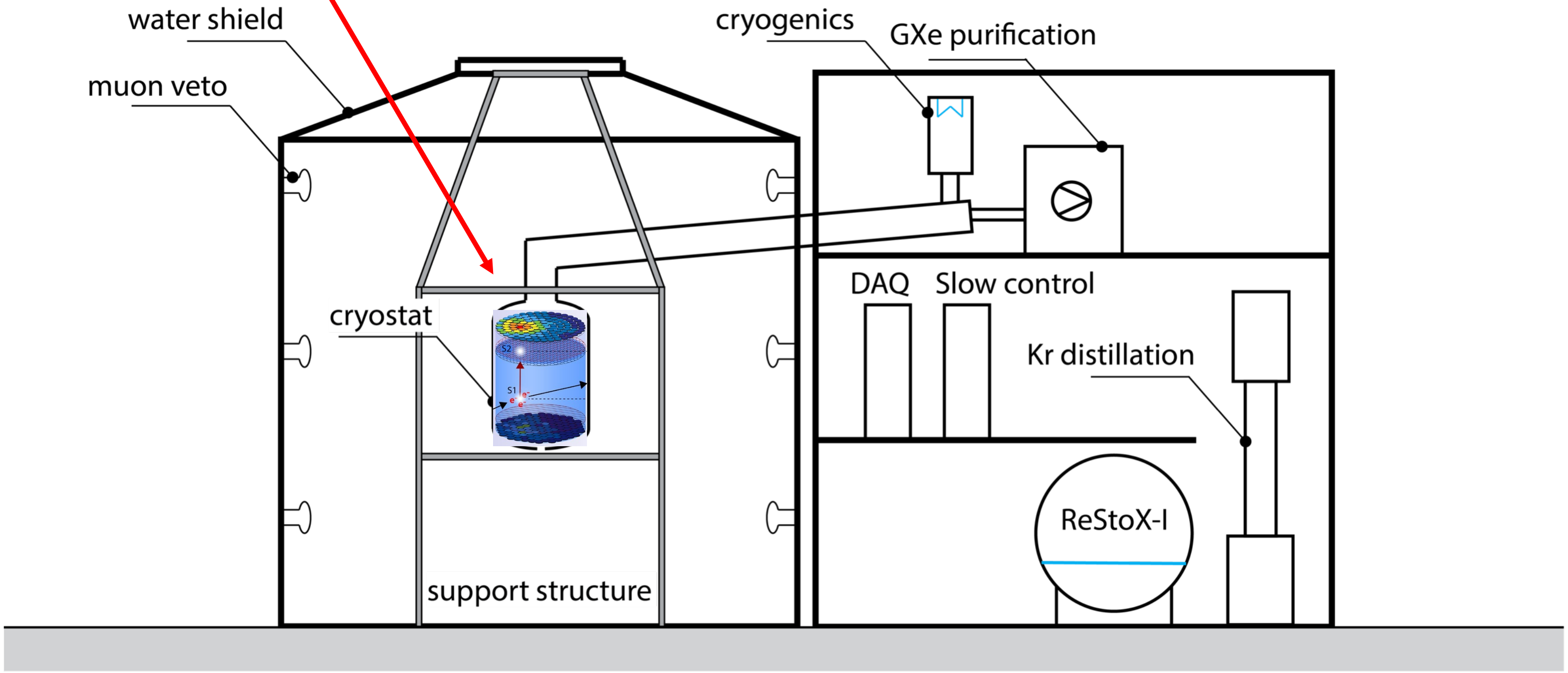
From XENON1T to XENONnT





From XENON1T to XENONnT

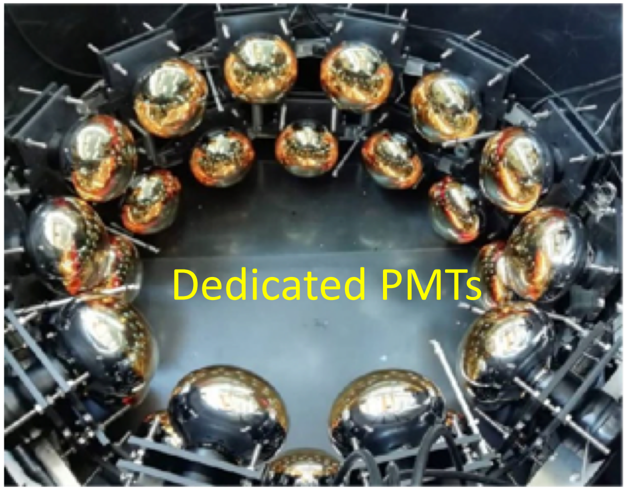
Larger TPC
- Total 8.4 t LXe
- 5.9 t in TPC
- ~ 4 t fiducial
- 248 → 494 PMTs

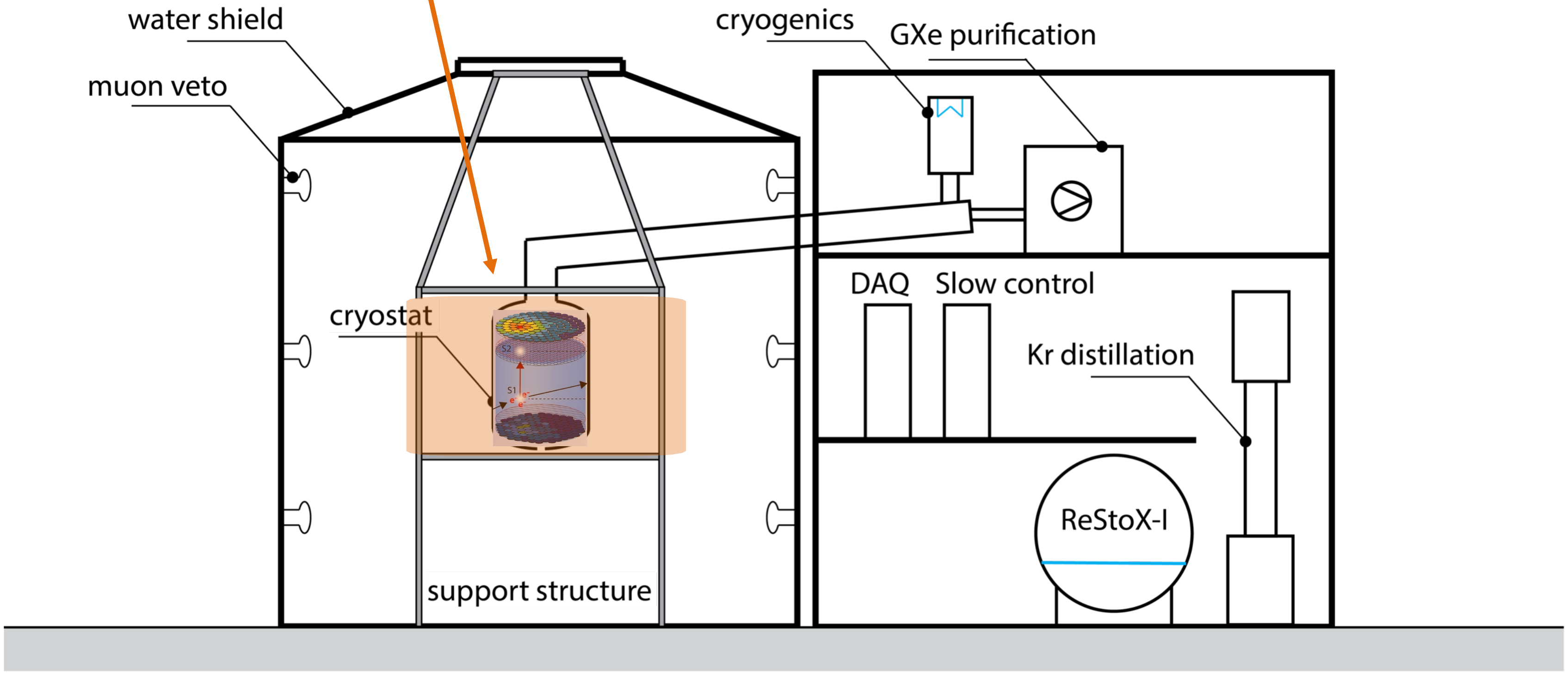


From XENON1T to XENONnT

Neutron Veto

- Inner region of existing muon veto
- optically separated
- 120 additional PMTs
- Gd in the water tank
- 0.5% $Gd_2(SO_4)_3$

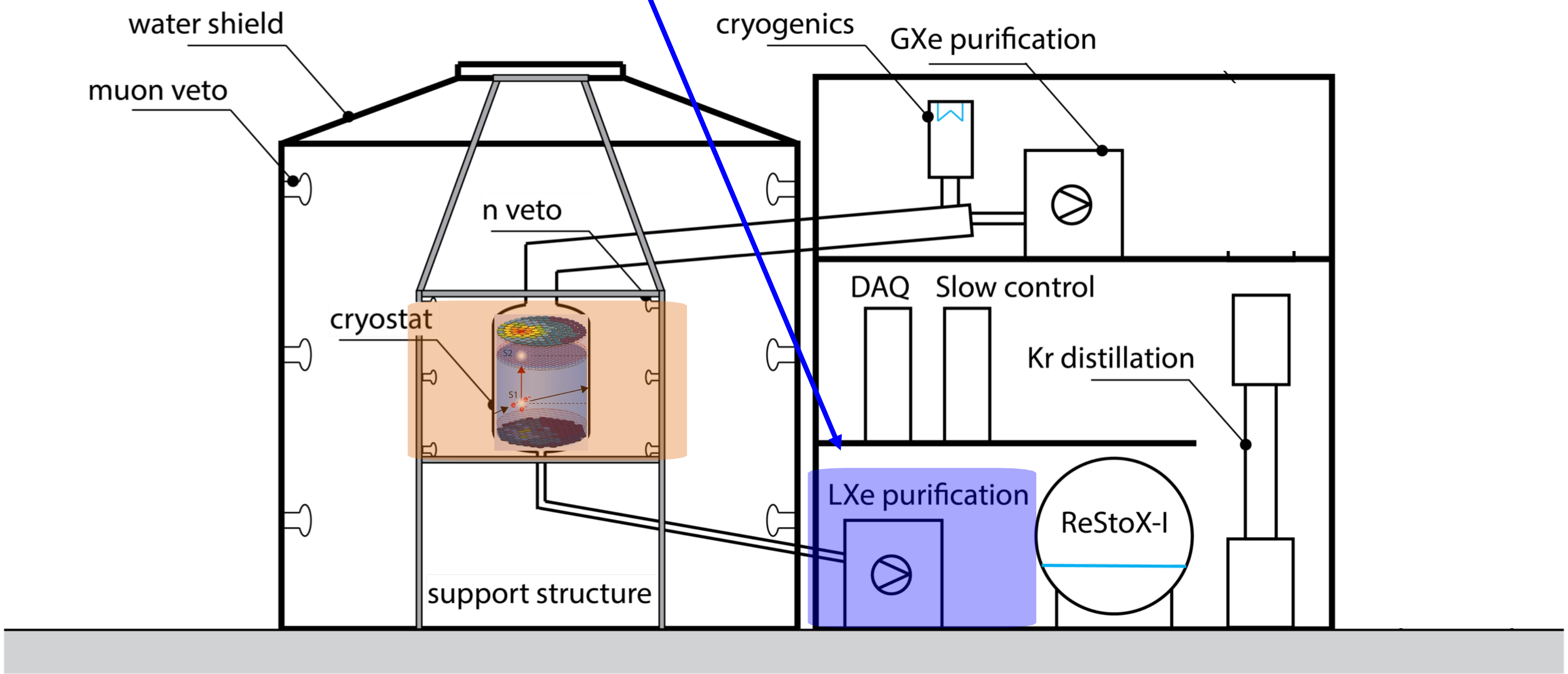




From XENON1T to XENONnT

LXe purification
- Faster xenon cleaning
- 5L/min LXe (2500 slpm)

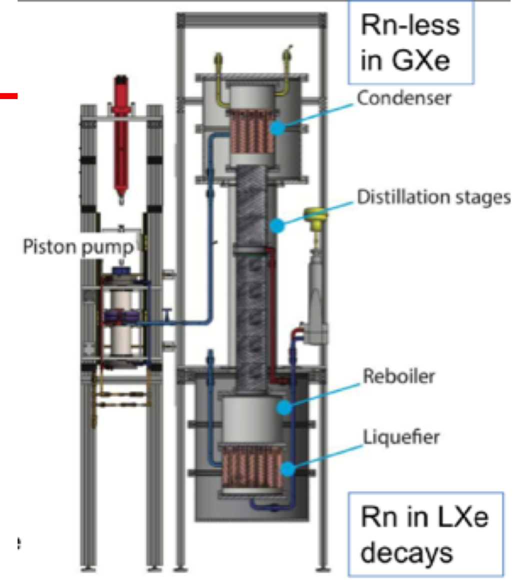
(XENON1T: 120 slpm)

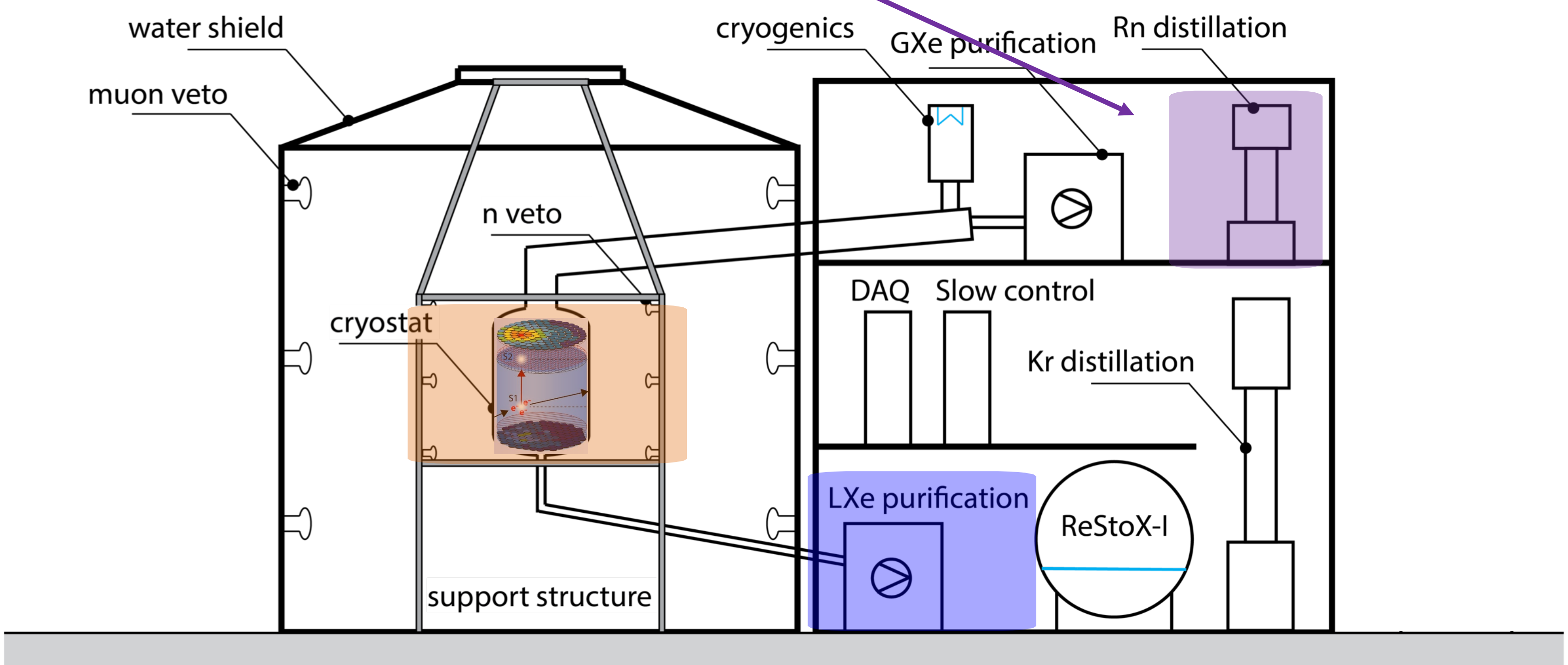


From XENON1T to XENONnT

222Rn Distillation

- Reduce radon from pipes, cables, cryogenic system
- New system, tested in XENON1T
- Reduction 1/10

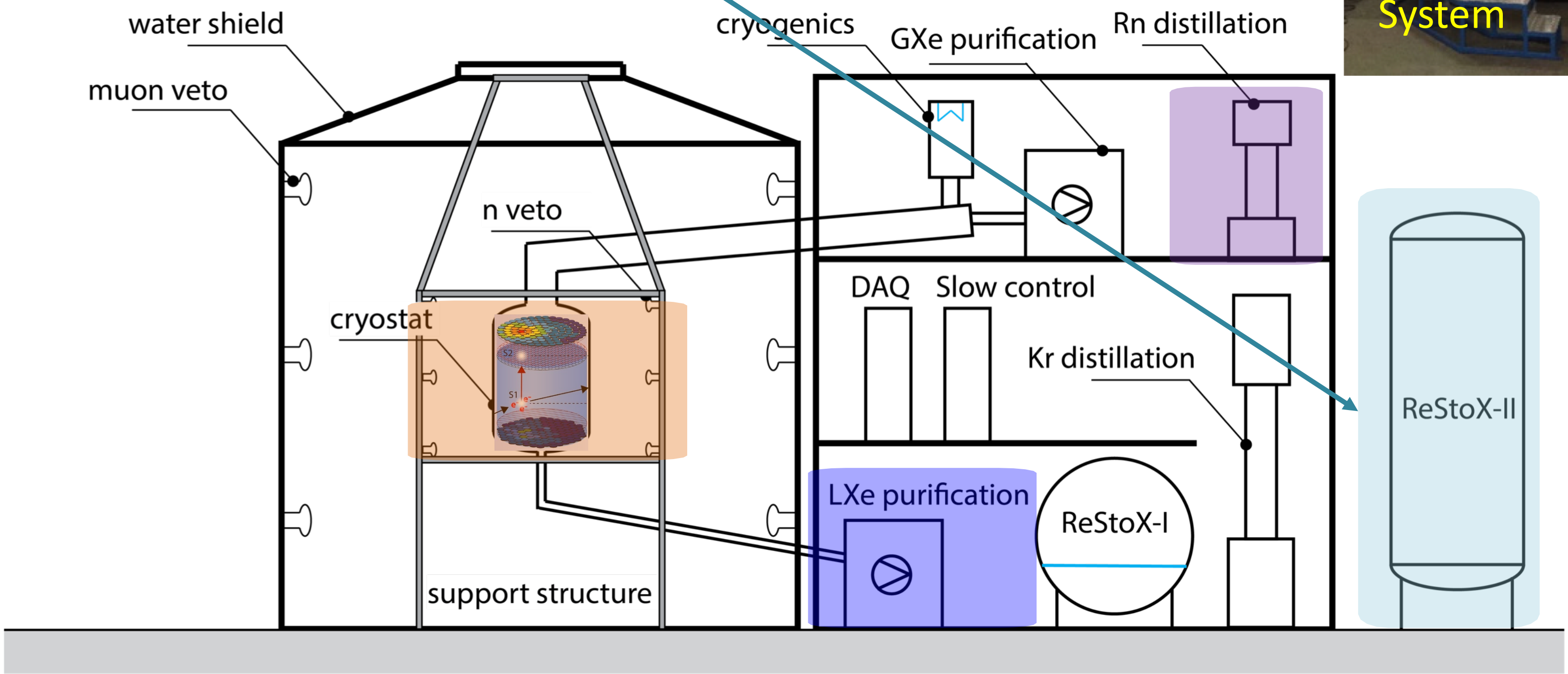




From XENON1T to XENONnT

Storage and Recovery (ReStoX-II)

- 10 tons capacity
- Storage in Solid / Liquid / Gas
- Fast recovery (1 ton / hour)



Conclusions

- **Strongest limit** on WIMP-nucleon SI cross-section above 6 GeV/c^2: minimum at $4.1 \cdot 10^{-47}$ cm^2 for a WIMP of 30 GeV/c^2
- Low Energy NR / ER analysis.
- Ongoing data analysis to investigate other new-physics channels: annual modulation, neutrinoless double beta decay,...
- Double Electron Capture detection : longest half-life ever measured directly
- Proof that xenon-based Dark Mater search experiments are sensitive for rare event searches
- **XENONnT will improve the sensitivity by another order of magnitude. First light in 2020.**